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Post-common envelope binaries from SDSS - XIV. The DR 7 white dwarf-main sequence binary catalogue

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ABSTRACT

We present an updated version of the spectroscopic white dwarf-main sequence (WDMS) binary catalogue from the Sloan Digital Sky Survey (SDSS). 395 new systems are serendipitous discoveries from the spectroscopic SDSS I/II Legacy targets. As part of SEGUE, we have carried out a dedicated and efficient (64 per cent success rate) search for WDMS binaries with a strong contribution of the companion star, which were underrepresented by all previous surveys, identifying 251 additional systems. In total, our catalogue contains 2248 WDMS binaries, and includes, where available, magnitudes from the GALEX All Sky Survey in the ultraviolet and from the UKIRT Infrared Sky Survey (UKIDSS) in the near-infrared. We also provide radial velocities of the companion stars, measured from the SDSS spectroscopy using the Na I $\lambda\lambda$ 8183.27,8194.81 absorption doublet and/or the Hα emission. Using an updated version of our spectral decomposition/fitting technique we determine/update the white dwarf effective temperatures, surface gravities and masses, as well as the spectral type of the companion stars for the entire catalogue. Comparing the distributions of white dwarf mass, temperature, and companion spectral type, we confirm that our SEGUE survey project has been successful in identifying WDMS binaries with cooler and more massive white dwarfs, as well as earlier spectral types than found previously. Finally, we have developed a publicly available interactive on-line data base for spectroscopic SDSS WDMS binaries containing all available stellar parameters, radial velocities and magnitudes which we briefly describe.

Key words: Binaries: spectroscopic – stars:low-mass – stars: white dwarfs – binaries: close – stars: post-AGB – stars: evolution variables

1 INTRODUCTION

Products of common envelope evolution play important roles in many areas of modern astronomy, e.g. stellar black hole binaries as laboratories for general relativity, double-degenerate white dwarf binaries as potential progenitors of type Ia supernovae, or double-degenerate neutron star binaries as progenitors of short gamma ray bursts. The fundamental concept of the formation of such systems is well established: once the more massive star in a main-sequence binary evolves into a red giant, unstable mass transfer is initiated at a rate that exceeds the Eddington limit of the companion star, and leads to the formation of a common envelope around the giant core and its less massive main sequence companion (Paczynski 1976; Webbink 1984; Iben & Tutukov 1986; Iben & Livio 1993). Drag forces between the binary components and the material of the envelope lead then to a dramatic decrease of the binary separation, and the orbital energy released due to the shrinkage of the orbit eventually expels the envelope exposing a post common-envelope binary (PCEB).

PCEBs continue to evolve to even shorter orbital periods through angular momentum loss given by magnetic braking and/or gravitational wave emission, and may either undergo a second common envelope, leading to double-degenerate PCEBs, or enter a semi-detached state and ap-

pear as cataclysmic variables, super-soft X-ray sources, or X-ray binaries. Because of the complex physical processes, and wide range of physical and time scales involved in the common envelope evolution, our understanding of this important phase is still very poor, and severely under-constrained by observations.

Among the variety of PCEBs, white dwarf-main sequence (WDMS) binaries are intrinsically the most common, and structurally simplest population, and hold a strong promise to provide crucial observational input that is necessary for improving the theory of close binary evolution (Schreiber & Gänsicke 2003). WDMS binaries descend from main sequence binaries where the primary has a mass $\lesssim 10M_{\odot}$. In the majority of cases ($\sim$3/4) the initial main sequence binary separation is large enough for the white dwarf precursor to evolve in the same way as a single star (de Kool 1992; Willems & Kolb 2004), and consequently the orbital period of these systems will increase because of the mass loss of the primary. In the remaining $\sim$1/4 of the cases, the system enters a common envelope, leading to a drastically shorter orbital period. The orbital period distribution of the entire population of WDMS binaries is therefore expected to be strongly bi-modal, with the short orbital period PCEBs clearly separated from the long orbital period WDMS binaries that did not undergo common envelope evolution. This seems to be confirmed by a recent high-resolution imaging campaign of 90 white dwarfs with known or suspected low-mass stellar and sub-stellar companions (Farihi et al. 2005, 2010).

The Sloan Digital Sky Survey (SDSS, York et al. 2000; Adelman-McCarthy et al. 2008; Abazajian et al. 2009) has been very efficient at identifying large numbers of WDMS binaries (Raymond et al. 2003; Silvestri et al. 2007; Heller et al. 2009), with 1602 systems in Data Release (DR) 6 (Rebassa-Mansergas et al. 2010). Intense radial velocity studies have led to the identification of a large number of PCEBs among the sample of SDSS WDMS binaries (Rebassa-Mansergas et al. 2007; Schreiber et al. 2008, 2010). A few examples of the work already done with both the entire sample of SDSS WDMS binaries, as well as the subset of systems identified to be PCEBs is the identification of many eclipsing PCEBs, important for testing the models of stellar structure (Pyrzas et al. 2009; Nebot Gómez-Morán et al. 2009; Parsons et al. 2010, 2011; Pyrzas et al. 2011); observational constraints on the efficiency of the common envelope (Zorotovic et al. 2010; De Marco et al. 2011); strong evidence for a discontinuity in the strength of magnetic braking near the fully convective boundary (Schreiber et al. 2010); and an unambiguous demonstration that the majority of low-mass (He-core) white dwarfs are formed in binaries (Rebassa-Mansergas et al. 2011).

Here, we present the final catalogue of WDMS binaries identified from SDSS (DR 7) spectroscopy, discuss the global properties of the 2248 systems, and describe a public interactive on-line data base of spectroscopic SDSS WDMS binaries.

2 FROM SDSS I TO SDSS II

During its first phase of operations, 2000 to 2005, SDSS-I mainly obtained spectra of galaxies and quasars selected from 5700 square degrees of imaging. The corresponding data largely dominate the DR 6 of SDSS (Adelman-McCarthy et al. 2008). From 2005 to 2008, SDSS-II carried out three distinct surveys:

- the Sloan Legacy Survey, that completed the original (mainly extragalactic) SDSS I imaging and spectroscopic goals;
- SEGUE, (the SDSS Extension for Galactic Understanding and Exploration, Yanny et al. 2009) that probed the structure and history of the Milky Way, obtaining additional imaging over a large range of galactic latitudes as well as spectroscopy for $\sim$ 240 000 stars;
- and the Sloan Supernova Survey, that carried out repeat imaging of the 300 square degree southern equatorial stripe to discover and measure supernovae and other variable objects.

The final data product of SDSS I and most of SDSS II is DR 7 (Abazajian et al. 2009). The different design of SDSS II and in particular the inclusion of a dedicated target selection for WDMS binaries in SEGUE significantly changes the resulting WDMS binary star content compared to DR 6. Below we review the two main channels that led to WDMS binary spectra taken by SDSS.

2.1 WDMS in SDSS I

The main science driver of SDSS I has been to acquire spectroscopy for magnitude-limited samples of galaxies (Strauss et al. 2002) and quasars (Richards et al. 2002). Because of their composite nature, WDMS binaries form a "bridge" in colour space that connects the white dwarf locus to that of low-mass stars (Smolčić et al. 2004). The blue end of the bridge, characterised by WDMS binaries with hot white dwarf and/or late type companions, strongly overlaps with the colour locus of quasars, and was therefore intensively targeted by SDSS spectroscopy. In contrast, the red end of the bridge is totally dominated by WDMS binaries containing cool white dwarfs, and excluded from the quasar program. Some additional WDMS binaries were directly selected for SDSS spectroscopy following the selection criteria of Raymond et al. (2003) and Silvestri et al. (2006). These criteria are based on the idea that a WDMS binary needs to be both red (main sequence) and blue (white dwarf), which is only true for a relatively small fraction of possible WDMS binary colours. In particular, systems in which one of the stellar components dominates the emission are excluded. In summary, the overall SDSS I spectroscopic sample of WDMS binaries (Raymond et al. 2003; Silvestri et al. 2007; Heller et al. 2009; Rebassa-Mansergas et al. 2010) is heavily biased against WDMS binaries containing cold white dwarfs and/or early-type secondaries, just as Schreiber & Gänsicke (2003) found for the pre-SDSS sample.

2.2 WDMS in SDSS II

Within SDSS II, the Legacy project is expected to identify WDMS binaries with similar properties, and at a similar rate

as within SDSS I. However, SEGUE included a small number of projects targeting specific classes of objects, and we have developed a colour selection to find WDMS binaries containing either cool white dwarfs and/or early M-dwarf/late K-dwarf companions, i.e. a population of WDMS binaries that has been consistently under-represented in the SDSS I and all the previous surveys.

To that end we simulated *ugriz* colours of WDMS binaries spanning a broad range in white dwarf effective temperatures ($T_{\rm wd} = 6000 - 40\,000$ K) and companion star spectral types (K0–M6) (see also Schreiber et al. 2007). Absolute Johnson *UBVRI* magnitudes for white dwarfs and for M/K dwarfs were taken from an updated version of Bergeron et al. (1995) and Pickles (1998), respectively. The combined *UBVRI* magnitudes were converted to *ugriz* using the empirical colour transformations of Jordi et al. (2006). Fig. 1 shows the loci of the synthetic SDSS WDMS binary colours in three different colour-colour diagrams ($u-g$ vs. $g-r$, $g-r$ vs. $r-i$, and $r-i$ vs. $i-z$) and demonstrates that systems dominated by the thermal flux of the secondary star can be separated from quasars (yellow dots), main sequence stars (grey dots), and WDMS binaries dominated by the thermal flux of the white dwarf by applying the following cuts:

$$\begin{array}{lcll}
u-g & < & 2.25 & g-r > -19.78(r-i)+11.13 \\
g-r & > & -0.2 & g-r < 0.95(r-i)+0.5 \\
g-r & < & 1.2 & i-z > 0.5 \ \text{for} \ r-i > 1.0 \\
r-i & > & 0.5 & i-z > 0.68(r-i)-0.18 \ \text{for} \ r-i <= 1.0 \\
r-i & < & 2.0 & 15 < g < 20.
\end{array}$$

These selection criteria (grey-shaded in Fig. 1) optimize the identification of WDMS binaries consisting of both cold white dwarfs and early type secondaries.

3 THE DR7 SDSS WDMS BINARY CATALOGUE

In this Section we describe the final spectroscopic DR 7 WDMS binary catalogue. It is important to keep in mind that the complete DR 7 catalogue will be formed by WDMS binaries identified in SDSS I and the Legacy survey in SDSS II, and by WDMS binaries identified within our SEGUE survey. In what follows we will denote the former as the SDSS I/II WDMS binary sample, the latter as the SEGUE WDMS binary sample.

We present first the outcome of the dedicated SEGUE WDMS binary survey and provide then a brief review of the WDMS binary search algorithm that we apply to the entire SDSS DR 7 spectroscopic data set (for details see Rebassa-Mansergas et al. 2010). Finally we estimate the completeness of the final SDSS DR 7 spectroscopy WDMS binary catalogue.

3.1 The SEGUE WDMS binary sample

In October 2005 SEGUE incorporated the colour selection given in the previous Section with the goal of targeting on average five, and at most ten WDMS binary candidates per plate-pair. In addition to the colour criteria we requested clean photometry for the selection of our targets. By the end of SDSS II in mid-2008, 116 plate-pairs and eight single plates including our WDMS binary target selection were observed in SEGUE (Table 1). However, during the early stages of SEGUE, 14 plate-pairs and two single plates (those < 2377 in Table 1) considered de-reddened *ugriz* magnitudes before applying our colour selection, resulting in a number of single (unreddened) foreground M-dwarfs being observed.

Using the DR 7 casjobs interface (Li & Thakar 2008)[1], we selected all point-sources within the footprint defined by the plates listed Table 1 that have clean photometry and satisfy our colour selection. This search resulted in 10505 unique point sources, of which 429 were followed-up spectroscopically. Among the 429 spectroscopic objects, we identified 274 as WDMS binaries, corresponding to a "hit-rate" of $\simeq 64$ per cent. Two additional WDMS binaries (SDSSJ135643.56–085808.9 and SDSSJ135930.96–101029.7) were found on plate 2716 that has not been published via DR 7, and 15 objects were found on the plates done with de-reddened magnitudes that do not satisfy our colour criteria. Cross-matching these 291 WDMS binaries with our DR 6 catalogue (Rebassa-Mansergas et al. 2010), we found that 40 systems had SDSS spectroscopy obtained as part of SDSS I/II, implying that ∼15 per cent of the targeted systems are duplicates. Hence, the number of genuinely new systems identified within SEGUE is 251.

The loci of the SEGUE WDMS binaries is shown in Fig. 1 in green, a few systems outside our colour selection (gray shaded area) are those found on the plates done with de-reddened magnitudes. WDMS binaries identified by our SEGUE survey are flagged as such in the last column of Table 6 in the Appendix.

3.2 The final DR 7 WDMS binary sample

We searched all new ∼0.4 million spectra from SDSS DR 7 for WDMS binaries following the template-fitting method outlined in Rebassa-Mansergas et al. (2010). We used as templates 163 previously identified WDMS binaries from Rebassa-Mansergas et al. (2010), spanning the whole range of white dwarf effective temperatures and companion star spectral types, and calibrated the constraints in both χ^2 and signal-to-noise ratio for each of them. We then visually inspected the selected WDMS binary candidates and divided the systems in three different categories: WDMS binary, white dwarf and M-dwarf. Given that visual inspection of WDMS binaries in which one of the stellar components dominates the SDSS spectrum can be misleading, we complemented the SDSS data with the photometry provided by the Galaxy Evolution Explorer (*GALEX*; Martin et al. 2005; Morrissey et al. 2005) and the UKIRT Infrared Sky Survey (UKIDSS; Dye et al. 2006; Hewett et al. 2006; Lawrence et al. 2007; Warren et al. 2007) and searched for blue (red) excess in the spectra classified as M-dwarf (white dwarf). All systems in which we detected either a blue or red excess were re-classified as WDMS binaries. Subsequently we inspected the SDSS images of our selected WDMS binary candidates, and excluded objects with morphologi-

[1] http://casjobs.sdss.org/CasJobs/

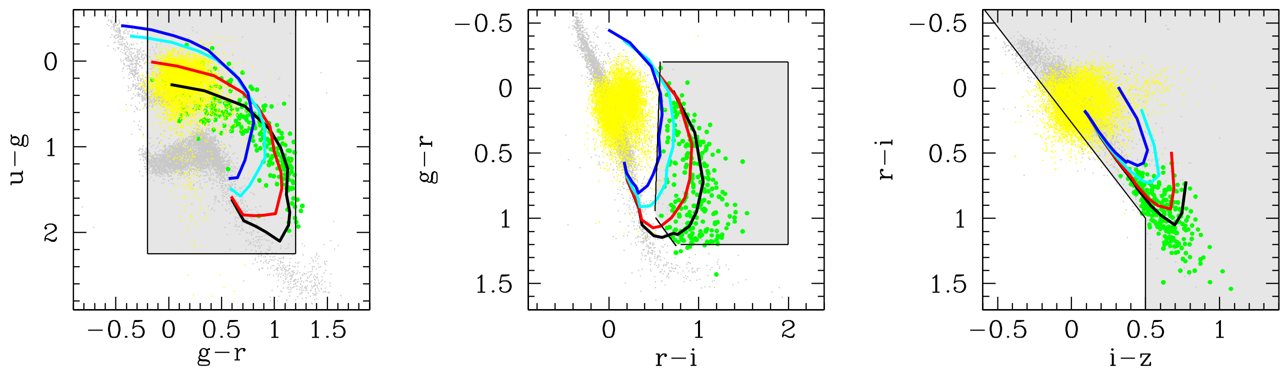

Figure 1. Synthetic WDMS binary colours in the $u-g$ vs. $g-r$ (left panel), $g-r$ vs. $r-i$ (centre panel), and $r-i$ vs. $i-z$ (right panel) colour-colour diagrams. Colour tracks are shown for WDMS binaries containing secondary star spectral types K0 to M6, as well as white dwarf effective temperatures of 40 000 K (blue), 30 000 K (cyan), 20 000 K (red), and 10 000 K (black). Colours for quasars and single main sequence stars are shown as yellow and gray dots respectively. In gray shaded we represent our selection criteria specially designed to identify WDMS binaries containing cold white dwarfs and/or early-type companions. The resulting sample of WDMS binaries identified by our selection criteria is represented by green dots.

Table 1. The list of 116 plate-pairs and eight single plates with WDMS target selection that have been observed in SEGUE.

2303/2318	2315/2330	2382/2402	2397/2417	2459/2474	2555/2565	2667/2671	2682/2700	2801/2822	2854/2869	2888/2913	2899/2924	2909/2934	2336
2304/2319	2316/2331	2383/2403	2441/2443	2537/2545	2556/2566	2668/2672	2683/2701	2803/2824	2855/2870	2889/2914	2901/2926	2910/2935	2337
2305/2320	2317/2332	2384/2404	2442/2444	2538/2546	2557/2567	2669/2673	2689/2707	2805/2826	2856/2871	2890/2915	2902/2927	2911/2936	2475
2306/2321	2334/2339	2386/2406	2445/2460	2539/2547	2558/2568	2670/2674	2690/2708	2806/2827	2857/2872	2891/2916	2903/2928	2938/2943	2552
2307/2322	2335/2340	2387/2407	2446/2461	2540/2548	2559/2569	2676/2694	2714/2729	2807/2828	2858/2873	2893/2918	2904/2929	2939/2944	2620
2308/2323	2378/2398	2389/2409	2447/2462	2541/2549	2621/2627	2677/2695	2724/2739	2812/2833	2859/2874	2894/2919	2905/2930	2940/2945	2865
2310/2325	2379/2399	2390/2410	2449/2464	2551/2561	2622/2628	2678/2696	2797/2818	2849/2864	2861/2876	2895/2920	2906/2931	2941/2946	2866
2312/2327	2380/2400	2393/2413	2452/2467	2553/2563	2623/2629	2680/2698	2798/2819	2852/2867	2862/2877	2897/2922	2907/2932	2963/2965	2942
2313/2328	2381/2401	2394/2414	2457/2472	2554/2564	2624/2630	2681/2699	2800/2821	2853/2868	2887/2912	2898/2923	2908/2933		

cal problems in their images. Finally, we cross-checked our list of WDMS binaries with the 1602 systems from DR 6 (Rebassa-Mansergas et al. 2010) as well as the 251 SEGUE WDMS binaries identified in Sect. 3.1. 390 genuinely new WDMS binaries were found in the Legacy part of DR 7, which in addition to the 251 systems identified in the SEGUE survey, bring the total number of new WDMS binaries in DR 7 to 641.

3.3 Catalogue completeness

Here, we analyse the completeness of the SEGUE WDMS binary sample within the survey footprint defined by the 240 spectroscopic plates listed in Table 1, as well as the completeness of the SDSS I/II WDMS binary sample.

We define the completeness of our SEGUE sample as the number of SEGUE WDMS binaries found by our template-fitting method (Sect. 3.2) that have colours satisfying our selection criteria (Eq. 1) divided by the number of all 274 SEGUE WDMS binaries found in Sect. 3.1. We find a completeness of 100 per cent, i.e. all SEGUE WDMS binaries were correctly identified by our template-fitting method.

To calculate the completeness of the SDSS I/II WDMS binary sample is not straightforward, as it becomes necessary to analyse the entire Legacy footprint. Such an endeavor is far away from the scope of this paper, however we can estimate the completeness by analysing photometric areas representative of the SDSS I/II WDMS binary population. For this purpose we used the three colour regions defined by Rebassa-Mansergas et al. (2010). For the DR 6 WDMS binary catalogue this resulted in a completeness of $\gtrsim$ 98 per cent (see Sect. 3 in Rebassa-Mansergas et al. 2010). Here, we identified only five additional WDMS binaries to the 390 identified in Sect. 3.2 that were not found by our template-fitting method, implying a completeness of $\gtrsim$ 98 per cent. The five systems are SDSS J001846.79+000237.6, SDSS J020756.15+214027.4, SDSS J133902.65+104136.3, SDSS J150538.90+563353.2, and SDSS J224122.87+010608.6. The spectra of these five objects are completely dominated by the flux of the secondary star, and only a mild blue excess is seen in the blue part of the spectra. Adding these five objects to our SDSS I/II sample increases the number of new spectroscopic WDMS binaries to 395. The *total* number of WDMS binaries in the entire SDSS DR 7 thus increases to 2248: 251 form the SEGUE WDMS binary sample, 1997 form the SDSS I/II WDMS binary sample (1602 within DR 6 identified by Rebassa-Mansergas et al. 2010, 395 identified in this work). Fig. 2 provides the position of the complete SDSS WDMS binary catalogue both in Galactic and equatorial coordinates, and an excerpt of the complete list can be found in Table 2 of the Appendix.

In summary, we conclude that we are confident to have identified nearly all ($\gtrsim$ 98 per cent) WDMS binaries within

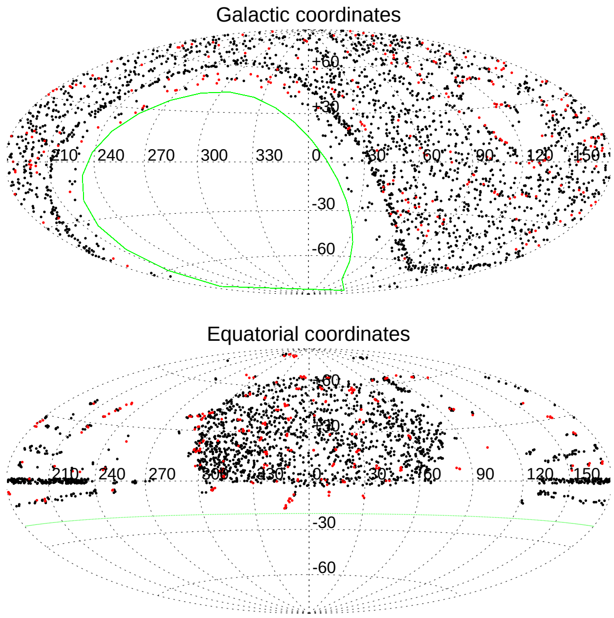

Figure 2. Position of SDSS I/II (black) and SEGUE (red) WDMS binaries in Galactic and equatorial coordinates.

the entire DR 7 spectroscopic data release, and that our SEGUE survey has been very efficient in identifying WDMS binaries within a colour space that has so far been neglected.

4 CHARACTERIZATION OF THE SDSS WDMS BINARY POPULATION

With more than 2000 systems and being $\gtrsim 98$ per cent complete, our spectroscopic DR 7 SDSS WDMS binary catalogue represents the so far largest and most homogeneous sample of compact binary stars. We here provide stellar parameters, distances, radial velocities and magnitudes for the complete DR 7 SDSS WDMS binary catalogue. Special attention is taken to characterise the differences between the SEGUE and the SDSS I/II WDMS binary samples.

4.1 Ultraviolet and near-infrared magnitudes

We cross-correlated our list of WDMS binaries with *GALEX* GR 6 (Martin et al. 2005; Morrissey et al. 2005), which provides an updated processing of the *GALEX* data compared to GR 4, which we used in Rebassa-Mansergas et al. (2010). Therefore, the *GALEX* ultraviolet magnitudes in this paper supersede those published in our latest WDMS binary catalogue. We also cross-correlated all WDMS binaries with UKIDSS DR 6 (Lawrence et al. 2007; Warren et al. 2007) to obtain near-infrared $yJHK$ magnitudes. Where available, *GALEX* and UKIDSS data are given in Table 4 of the Appendix together with the $ugriz$ SDSS magnitudes.

4.2 Radial velocities

We measured radial velocities from the available SDSS sub-spectra[2], as well as from the average SDSS spectra. Radial velocities were measured fitting two Gaussians of fixed separation but free individual widths and amplitudes to the Na I $\lambda\lambda$ 8183.27,8194.81, and/or a Gaussian to the Hα emission line (see Rebassa-Mansergas et al. 2008 for details). See Table 3 in the Appendix for the heliocentric corrected dates of the observations and the corresponding radial velocities.

4.3 Stellar parameters

In order to determine the stellar parameters of our SDSS WDMS binaries we used the spectral decomposition/fitting routine described in Rebassa-Mansergas et al. (2007, 2010). Intensive tests of our white dwarf fitting procedure using SDSS spectra of single white dwarfs revealed that we overestimated the errors on the white dwarf parameters by a factor ~ 2 in our previous SDSS WDMS binary studies (Rebassa-Mansergas et al. 2011), we hence re-fitted the spectra of all SDSS WDMS binaries to obtain more realistic uncertainties of the white dwarf parameters.

Our fitting routine follows a two-step procedure. Firstly, a given SDSS WDMS binary spectrum is fitted with a two-component model using the M dwarf and white dwarf templates of Rebassa-Mansergas et al. (2007). We used an evolution strategy (Rechenberg 1994) to decompose the WDMS binary spectra into their two individual stellar components. In brief, this method optimises a fitness function, in this case a weighted χ^2, and allows an easy implementation of additional constraints, such as e.g. the inclusion of a Gaussian fit to the Balmer emission lines. From the converged white dwarf plus M-dwarf template fit to each WDMS spectrum we recorded the spectral type of the secondary star, as well as the flux scaling factor between the M-star template and the observed spectrum. Subsequently, the best-fit M-dwarf template, scaled by the appropriate flux scaling factor, is subtracted from the SDSS spectrum, and the residual white dwarf spectrum is fitted with a model grid of DA white dwarfs (Koester et al. 2005). More specifically, we fit the the normalised Hβ to Hϵ line profiles to determine the white dwarf effective temperature and surface gravity ($\log g$). We exclude Hα from this fit as it is in many cases contaminated by the flux residuals of the M-dwarf. The equivalent widths of the Balmer lines go through a maximum near $T_{\rm eff} = 13\,000$ K, with the exact value being a function of $\log g$. Therefore, $T_{\rm eff}$ and $\log g$ determined from Balmer line profile fits are subject to an ambiguity, often referred to as "hot" and "cold" solutions. This degeneracy is broken fitting also the entire white dwarf spectrum (continuum plus lines), excluding only wavelengths > 7150 Å (again to minimise contamination by flux residuals from M dwarf companion). The slope of the white dwarf spectrum is mostly sensitive to $T_{\rm eff}$, and the best-fit value from the entire spectrum is then used to choose between the hot and cold solution. All fits are visually inspected, and, where available, the choice of hot vs. cold solution is further guided by comparison of

[2] Each SDSS spectrum is the result of averaging several (typically three) individual exposures, or sub-spectra.

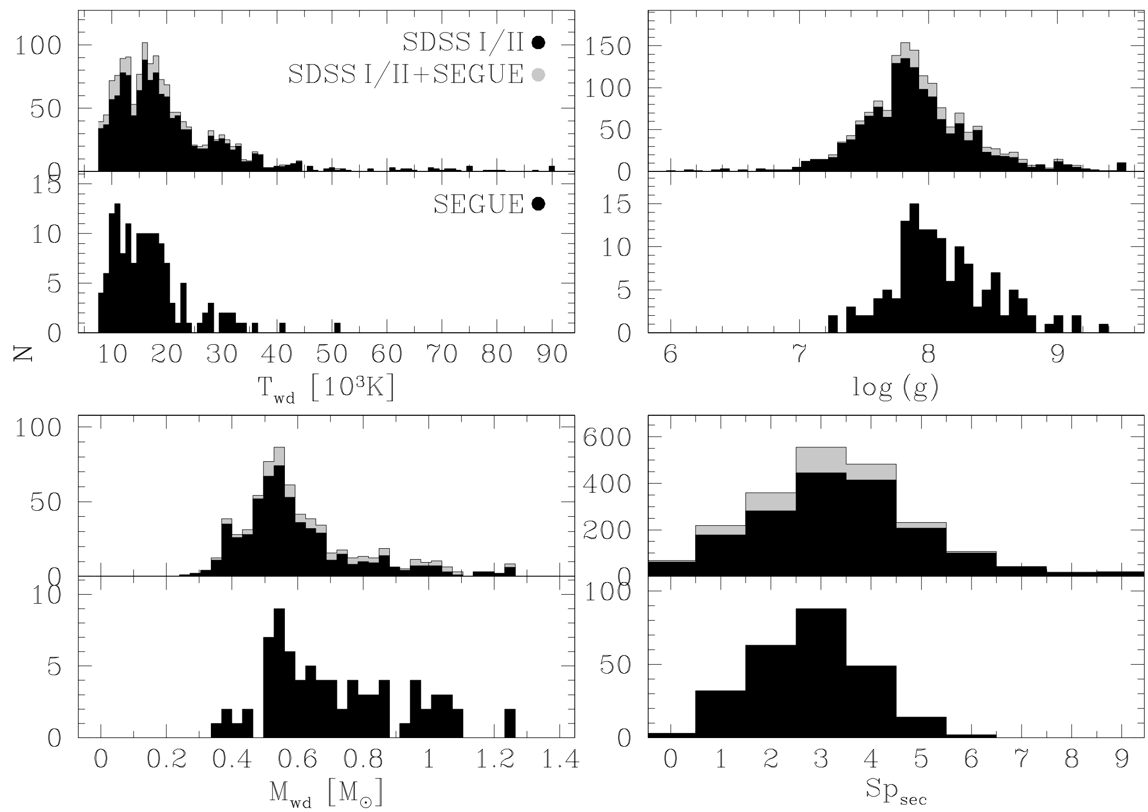

Figure 3. Distributions of white dwarf effective temperatures (top left), surface gravities (top right) and masses (bottom left), and spectral type of the companions (Sp_{sec}, bottom right). Top panels show in black and gray the SDSSI/II and SDSSI/II plus SEGUE WDMS binary distributions. Bottom panels show in black the parameter distributions of the SEGUE WDMS binary sample.

the predicted ultraviolet fluxes to *GALEX* measurements. From an empirical spectral type-radius relation for M-dwarfs (Rebassa-Mansergas et al. 2007) and a mass-radius relation for white dwarfs (Bergeron et al. 1995; Fontaine et al. 2001) we calculate then the radius of the secondary star and the mass and the radius of the white dwarf respectively. From the radii and the flux scaling factors between the WDMS binary components and the white dwarf models and main sequence star templates, we finally obtain two independent distances.

From the total list of parameters we selected a "clean" list by applying the following restrictions. As a systematic increase in the surface gravity for white dwarfs below ∼12000 K has been observed in recent white dwarf studies (e.g. Koester et al. 2009), we only consider white dwarf masses and gravities if the white dwarf temperature exceeds this value. In order to avoid contamination from unreliable stellar parameters, we additionally only consider objects with a relative error in the white dwarf parameters of less than 15 per cent. For the SDSSI/II WDMS binary sample, this resulted in 1378, 1278 and 579 WDMS binaries in the distributions of white dwarf effective temperatures, surface gravities and masses respectively (top panels in Fig. 3, black). For the SEGUE sample the distributions contain 143, 144 and 79 WDMS binaries respectively (bottom panels in Fig. 3, black). The spectral types of the secondary stars are directly determined from the spectral template fitting. For the SDSSI/II and SEGUE sample, 1768 and 251 WDMS binaries containing M-dwarfs have reliable spectral types, respectively, and are included in the distribution.

The stellar parameter distributions of the complete SDSS WDMS binary sample (SDSSI/II plus SEGUE) are shown in gray in the top panels of Fig. 3 and the cumulative distributions of the SDSS I/II and the SEGUE sample are shown in Fig. 4.

It is very clear that the stellar parameters of the SDSSI/II WDMS binary sample differ from those in the SEGUE WDMS binary population (black distributions Fig. 3). Kolmogorov-Smirnov and χ^2 (in case of the spectral type distributions) tests applied to the cumulative stellar parameter distributions in both sub-samples gave probabilities $< 10^{-4}$ in all cases, clearly indicating that the two populations are different. These differences have a straight forward explanation. WDMS binaries detected within our SEGUE survey (Sect. 2.2) are by definition of the selection criteria considerably less blue than WDMS binaries from SDSSI/II. This favours the detection of WDMS containing cold and massive (and hence small) white dwarfs and early M spectral types:

- The upper left panel of Fig. 4 shows the white dwarf ef-

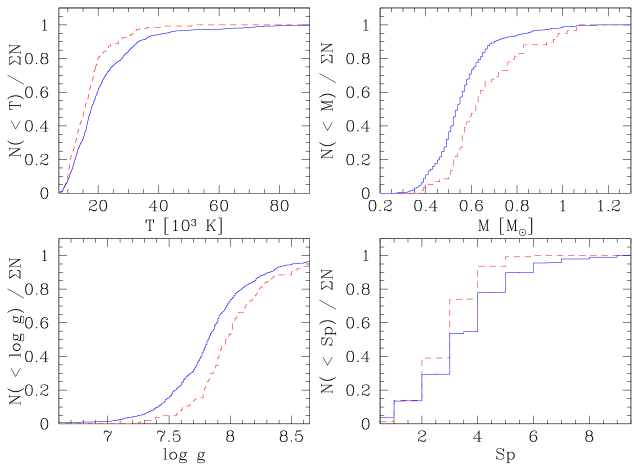

Figure 4. White dwarf effective temperature (top left), surface gravity (top right) and mass (bottom left), and spectral type of the companion (Sp_{sec}, bottom right) cumulative distributions obtained from the SDSSI/II sample of WDMS binaries (solid blue lines), and those WDMS binaries identified within SEGUE (red dashed lines).

fective temperature cumulative distributions. Inspecting the Figure it becomes clear that the number of cold white dwarfs is significantly higher in our SEGUE WDMS binary sample.

- The upper right and lower left panels of Fig. 3 and Fig. 4 clearly show that the SEGUE sample contains more systems with massive white dwarfs with a higher surface gravity.
- The secondary star spectral type distributions are provided in the bottom right panel of Fig. 4 and Fig. 3. As a natural consequence of our selection criteria (Sect. 2.2), the sample of SEGUE WDMS binaries contains more secondary stars of spectral types M0-6.

The comparison of the SDSS I/II and SEGUE WDMS binary samples clearly demonstrates that our selection criteria (Eq. 1) was efficient at identifying WDMS binaries containing cold/massive white dwarfs and early type secondary stars, i.e. a population that has been underrepresented by all previous surveys.

4.4 Distances

Two independent distances have been determined for each system from the flux scaling factors between the model (template) fit and the observed fluxes, and the use of a mass-radius relation for white dwarfs and an empirical spectral type-radius relation for M-dwarfs. The obtained distances are compared here. To avoid statistical and systematic uncertainties in the comparison we require the relative error in the white dwarf distances ($d_{\rm WD}$) to be less than 15 per cent, the effective temperature of the white dwarfs to exceed 12 000 K, and exclude systems with indications for both components being resolved on the SDSS image [3]. The relative error in the secondary star distance ($d_{\rm sec}$) is dominated by the scatter in the empirical M-dwarf spectral type-radius relation (Rebassa-Mansergas et al. 2007, see their Fig. 7), which represents an intrinsic uncertainty rather than a statistical error in the fit, and we consequently do not apply any error cut in $d_{\rm sec}$. Fig. 6 provides $d_{\rm WD}$ as a function of $d_{\rm sec}$ for the resulting 575 SDSSI/II (top panel) and 65 SEGUE (bottom panel) WDMS binaries.

An effect previously identified by Schreiber et al. (2008); Rebassa-Mansergas et al. (2010) can be seen in the SDSSI/II sample (Fig. 6 top panel): for 27.0 ± 2 per cent of the systems the two distance estimates disagree at a 1.5σ significance level (red points in Fig. 6), with the vast majority (21.4 ± 2 per cent) of these having $d_{\rm sec} > d_{\rm WD}$ outliers. Only relatively few systems are found significantly below $d_{\rm sec} = d_{\rm WD}$ (5.6 ± 1 per cent). Conversely, the fraction of 1.5σ outliers in the SEGUE WDMS binary sample (Fig. 6 bottom panel) not only decreases but is almost identical above (10.7 ± 3.5 per cent) and below (9.2 ± 3.6 per cent) $d_{\rm sec} = d_{\rm WD}$.

Rebassa-Mansergas et al. (2007) interpreted the $d_{\rm sec} > d_{\rm WD}$ outlier effect as resulting from magnetic activity affecting the surface of the secondary stars. If this was the case, the fraction of active secondary stars in the SEGUE WDMS binary sample should be significantly smaller. One might intend to interpret this as being a consequence of the SEGUE WDMS binaries being, on average, older (since the white dwarfs forming the SEGUE sample are systematically cooler, see Fig. 4), as it has been demonstrated that older M-dwarfs are systematically less active (West et al. 2008). However, as we are considering only systems with white dwarf effective temperatures exceeding 12 000 K (Fig. 6), this age-effect is expected to be negligible.

To investigate this quantitatively, we have estimated the ages of the WDMS binaries of the SDSS I/II and SEGUE subsamples in Fig. 6 and compared them to the activity lifetimes of West et al. (2008). The total age of each system is given by the sum of the white dwarf cooling age and the main sequence lifetime of the white dwarf progenitor. White dwarf cooling ages were calculated from the cooling tracks of Althaus & Benvenuto (1997). Main sequence progenitor lifetimes were obtained from the equations of Tuffs et al. (2004, see their Appendix), where the main sequence progenitor masses were calculated using the initial-to-final mass relation by Catalán et al. (2008). A relatively large per-

Table 2. Percentage of WDMS binary ages for the SDSS I/II and SEGUE samples defined in Section 4.4 that are above and below the activity lifetimes estimated by West et al. (2008) as a function of spectral type.

Sp. type	Act. lifet.	SDSS I/II		SEGUE	
		>act. lifet	<act. lifet	>act. lifet	<act. lifet
	[Gyr]	per cent	per cent	per cent	per cent
M0	0.8± 0.6	60	40	-	-
M1	0.4± 0.4	6	94	0	100
M2	1.2± 0.4	42	58	37	64
M3	2.0± 0.5	57	43	69	31
M4	4.5± 0.5	97	3	100	0
M5	7.0± 0.5	100	0	100	0
M6	7.0± 0.5	100	0	-	-

[3] The flux contribution of one or both stars in a resolved WDMS binary spectrum is likely to be underestimated and this translates into an underestimated flux scaling factor and overestimated distance.

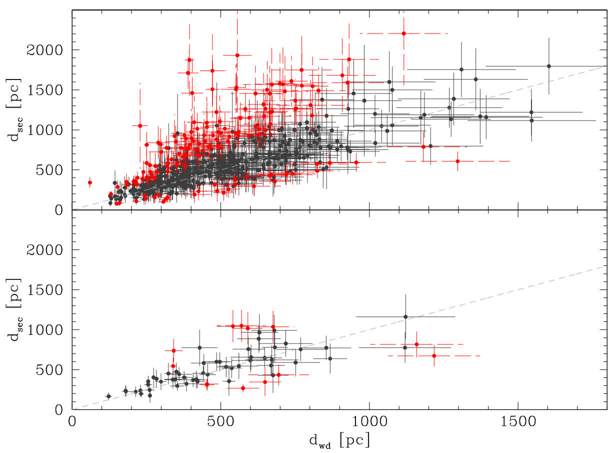

Figure 5. Secondary star distances as a function of white dwarf distances for a sub-sample of 575 SDSSI/II (top panel) and 65 SEGUE (bottom panel) WDMS binaries in which the white dwarf distance relative error is less than 15 per cent. In red 1.5σ outliers from $d_{\rm sec} = d_{\rm WD}$ (gray dashed line).

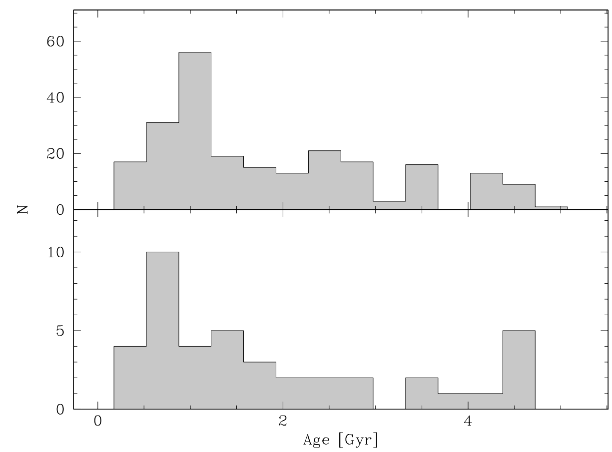

Figure 6. Distribution of WDMS binary ages for a sub-sample of 231 SDSSI/II (top panel) and 41 SEGUE (bottom panel) systems. See Section 4.4 for details.

centage of WDMS binaries are PCEBs (Schreiber et al. 2010), for which the initial-to-final mass relation for single white dwarfs is generally not valid. However, Zorotovic et al. (2011, their Fig. 9) demonstrated that this relation is a good approximation for PCEBs between 0.55 and 0.8$M_{\odot}$, as the core of the progenitors of such white dwarfs is almost entirely developed at the onset of common envelope evolution. We therefore considered only systems containing white dwarfs with masses in this range. The estimated ages are compared to the activity lifetimes of West et al. (2008) in Table 2, where we provide the percentages of systems with ages above and below the activity lifetime for different spectral types. For completeness, the estimated ages are also illustrated in Fig. 6. The fractions of systems that should be active according to their age are very similar for WDMS binaries in both samples (Table 2), i.e. 28$\pm$3 per cent (SDSS I) and 31$\pm$7 per cent (SEGUE). Thus, the two samples should also contain approximately the same number of $d_{\rm sec} > d_{\rm WD}$ outliers if those are caused by activity. This is apparently not the case (Fig. 6) and we conclude that the SEGUE data questions our previous interpretation of magnetic activity causing the distance disagreement, and that this discrepancy remains an unsolved issue. Using model spectra (e.g. PHOENIX, Hauschildt & Baron 1999) instead of M-dwarf templates in the decomposition/fitting of the SDSS WDMS binary spectra and comparing both results may provide useful insights (e.g. Heller et al. 2009).

5 THE SDSS WDMS BINARY ON-LINE DATA BASE

We have presented an updated version of the spectroscopic SDSS WDMS binary catalogue incorporating 646 new systems from the DR 7 spectroscopic data base (Sect. 3). A significant fraction of the new systems (251) have been identified by our SEGUE WDMS binary survey (Sect. 2.2). The entire DR 7 SDSS WDMS binary catalogue contains now 2248 objects, each of them associated to a large number of stellar parameters, radial velocities and photometric magnitudes. Given the large amount of available information we developed an SQL (Structured Query Language) interactive on-line data base for spectroscopic SDSS WDMS binaries. This data base is open for the general public, however permission to update the data base will be restricted to our team.

The data base allows the user to search for information in three different ways and is based on six different tables that form the SQL's db. In the following we provide instructions on how to use the interactive SDSS WDMS binary data base and give details on the content of each table. More detailed information and examples can be found on the web page *http://www.sdss-wdms.org.*

5.1 Tables description

Each of the SDSS WDMS binaries in our catalogue has been given an identification number (ID), ranging from 1 to 2248. This ID is unique for each object. In addition we have named our systems by their International Astronomical Union (IAU) name, i.e. SDSSJHHMMSS.SS$\pm$DDMMSS.S, as well as by an abbreviated form, i.e. SDSSJHHMM$\pm$DDMM. On the SQL's db the table *obj_iau_name* contains the ID and the IAU name of the 2248 WDMS binaries, the table *object* contains both the ID and the abbreviated names. The ultraviolet *GALEX* DR 6, the *ugriz* SDSS and the near-infrared UKIDSS DR 6 magnitudes plus photometric errors, as well as the right ascensions and declinations of our targets are stored in the table *magnitudes*. The measured Na I absorption doublet and Hα emission radial velocities and corresponding errors, together with the heliocentric corrected dates of the observations can be found in the table *rv*. To these radial velocities we added the measurements presented in Schreiber et al. (2010) and Nebot Gomez-Moran et al. (2011, submitted). The stellar parameters together with the SDSS identifiers (i.e. modified Julian date, MJD, plate, PLT and fibre, FIB), the distances, and the WDMS binary spectral types are given in the table *wdms*. Finally the average stellar parameters (for several objects multiple SDSS spec-

tra are available) and those derived from additional follow-up observations performed by us are provided in the table *mean_param*. The six tables are linked using the IAU names and excerpts of each table can be found in the Appendix A.

5.2 Queries

The just described data base can be searched in three different ways.

- *Search by object*. This option allows the user to obtain all available information for a specific object or a list of objects using either the IAU or the abbreviated identifiers. The provided information for each system includes *ugriz* SDSS, ultraviolet DR 6 *GALEX* and near infra-red DR 6 UKIDSS magnitudes (when available), the binary and stellar parameters as well as the SDSS image and spectrum, the two component fits to the SDSS WDMS binary spectrum, and the model fit to the residual white dwarf spectrum as obtained from our decomposition/fitting routine.
- *Search by parameter*. The user may define constraints on a chosen set of parameters to obtain a list of objects that satisfy user defined conditions. Such constraints can be applied to all the stellar parameters, magnitudes and radial velocities, as well as coordinates and PCEB orbital periods. To provide access to the results of our follow-up studies, we have additionally defined the following parameters: (1) *sigma*, set to 3 or 4 depending on whether we detect 3σ or 4σ radial velocity variations, set to 0 when no radial velocity variations are detected, set to -1 when no information is available (in other words $sigma = 3, 4$ stands for a PCEB, $sigma = 0$ for a wide WDMS binary candidate); (2) *re*, set to 1 for resolved objects in the SDSS images, set to 0 for non-resolved objects; (3) *spec*, set to 1 for objects with available follow-up spectroscopy, set to 0 for objects we did not follow-up; (4) *phot*, set to 1 for objects with available follow-up photometry, set to 0 for objects we did not follow-up; (5) *segue*, set to 1 if the considered WDMS binary was identified by our dedicated SEGUE survey, set to 0 otherwise.
- *Manual search*. The user may run his own SQL scripts on the six tables introduced in Sect. 5.1. For example, if the user wishes to search for WDMS binaries identified as PCEBs with at least one of the Na I doublet radial velocity measurements above 100 km s^{-1}, no available photometric observations, SDSS i-magnitudes of less than 18.5, with declinations between 0 and 30 degrees, and white dwarf mass errors less than 0.1 M$_\odot$, the user should type the following:

```
select
s.iau_name, s.mwde, f.i, p.rv_na
from
mean_param as s, rv as p, magnitudes as f
where
s.iau_name = p.iau_name
and s.iau_name = f.iau_name
and p.rv_na > 100
and s.sigma > 0
and phot = 0
and Mwde between 0.0001 and 0.1
and f.i < 18.5
and f.decl between 0 and 30
```

6 SUMMARY

We have identified 646 new spectroscopic SDSS WDMS binaries; 395 have been detected within the spectroscopic SDSS I/II Legacy Survey, the remaining 251 new discoveries result from an efficient (64 per cent success rate) survey carried out by us within SEGUE. This survey has been designed to detect a population of WDMS binaries containing cold white dwarfs and/or early type companion stars, a population of WDMS binaries clearly underrepresented in all previous WDMS binary samples. The total number of spectroscopic SDSS WDMS binaries increased to 2248, and we expect this final DR 7 SDSS WDMS binary catalogue to be $\gtrsim$98 per cent complete. Using an updated version of our decomposition/fitting routine we have determined/updated the stellar parameters of the complete SDSS WDMS binary catalogue. Comparing the parameter distributions of the SDSS I/II and SEGUE WDMS binary samples, we demonstrated that our SEGUE survey indeed has been very efficient at identifying WDMS binaries containing cold white dwarfs. The DR 7 WDMS binary catalogue represents the largest and most homogeneous sample of compact binary stars presented so far and an excellent basis for further follow-up studies. This potential can now be explored easily using our new user-friendly interactive on-line data base of SDSS WDMS binaries containing all available stellar parameters, radial velocities and magnitudes, now publicly available at *http://www.sdss-wdms.org*.

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APPENDIX A: EXCERPTS OF SQL TABLES

We provide here excerpts for the six tables on our interactive on-line data base. The complete tables are available on *http://www.sdss-wdms.org*.

Table A1. Table *object*. Contains the identification number (ID) and abbreviated name for the complete catalogue.

ID	abbreviated name
0001	SDSSJ0001+0006
0002	SDSSJ0004–0020
0003	SDSSJ0006+0034
0004	SDSSJ0010+0031
0005	SDSSJ0012+0010

Table A2. Table *object_iau_name*. Contains the identification number (ID) and international astronomical union name for the complete catalogue.

ID	IAU name
0001	SDSSJ000152.09+000644.7
0002	SDSSJ000442.00–002011.6
0003	SDSSJ000611.93+003446.5
0004	SDSSJ001029.87+003126.2
0005	SDSSJ001247.18+001048.7

Table A3. Table *rv*. Contains the measured Na I absorption doublet and Hα emission radial velocities and corresponding errors, together with the heliocentric Julian dates (HJD) of the observations and the telescope used for obtaining the spectra. We indicate by '-' that no radial velocity values are available.

IAU name	HJD	RV_{Na} [$km\,s^{-1}$]	error [$km\,s^{-1}$]	$RV_{H\alpha}$ [$km\,s^{-1}$]	error [$km\,s^{-1}$]	telescope
SDSSJ000152.09+000644.7	2451791.8092	0.70	21.10	24.20	16.70	SDSS
SDSSJ001247.18+001048.7	2452519.8962	-	-	12.30	18.60	SDSS
SDSSJ001247.18+001048.7	2452518.9219	-14.30	30.10	30.60	14.40	SDSS
SDSSJ001359.39-110838.6	2452138.3933	28.90	16.90	0.00	0.00	SDSS
SDSSJ001726.63-002451.1	2452559.7852	-33.70	15.50	-30.10	11.40	SDSS

Table A4. Table *magnitudes*. Contains the right ascensions and declinations, as well as the ultraviolet *GALEX* DR 6, SDSS and near-infrared UKIDSS DR 6 magnitudes plus photometric errors. We indicate by '-' that no magnitudes are available. The errors have not been included here but are available on *http://www.sdss-wdms.org*.

IAU name	ra [deg]	dec [deg]	nuv	fuv	u	g	r	i	z	y	J	H	K
SDSSJ000152.09+000644.7	0.46704	0.11242	18.458	17.903	19.031	18.617	17.946	17.501	17.251	16.513	16.059	15.40160	15.289
SDSSJ000442.00–002011.6	1.17500	-0.33656	-	-	23.723	20.389	19.138	18.656	18.284	-	-	-	-
SDSSJ000611.93+003446.5	1.54975	0.57958	21.780	0.000	21.383	20.926	20.129	19.005	18.381	17.536	17.056	16.58058	16.201
SDSSJ001029.87+003126.2	2.62446	0.52394	20.178	19.964	21.929	20.853	19.975	19.001	18.421	17.659	17.147	16.52821	16.363
SDSSJ001247.18+001048.7	3.19658	0.18019	20.509	20.711	20.734	20.216	19.664	18.634	17.965	17.093	16.601	16.13305	0.000

Table A5. Table *wdms*. Contains the stellar parameters for both components, the identifiers for SDSS spectra (MJD, PLT, FIB), and spectral types of our WDMS binaries (see Rebassa-Mansergas et al. 2010 for a description). The secondary star masses and radii ($M_{\rm sec}$ and $R_{\rm sec}$) are obtained from the $Sp - M - R$ relation by Rebassa-Mansergas et al. (2007). We provide the two white dwarf solutions as obtained from our decomposition/fitting routine. The adopted solution is given by 1 in the first column, the ruled out solution by 0. The error parameters have not been included here but are accessible on *http://www.sdss-wdms.org*.

sol	IAU name	type	MJD	PLT	FIB	$T_{\rm eff}$(wd) [K]	$\log g$	$M_{\rm wd}$ [$M_\odot$]	$R_{\rm wd}$ [$R_\odot$]	$d_{\rm wd}$ [pc]	Sp	$M_{\rm sec}$ [$M_\odot$]	$R_{\rm sec}$ [$R_\odot$]	$d_{\rm sec}$ [pc]
1	SDSSJ001726.63-002451.1	DA/M	52559	1118	280	15601	7.800	0.510	0.01479	504	4	0.319	0.326	477
0	SDSSJ001726.63-002451.1	DA/M	52559	1118	280	12681	8.060	0.640	0.01243	345	4	0.319	0.326	477
1	SDSSJ001726.63-002451.2	DA/M	52518	0687	153	13588	8.110	0.680	0.01203	374	4	0.319	0.326	503
0	SDSSJ001726.63-002451.2	DA/M	52518	0687	153	15422	8.050	0.640	0.01258	418	4	0.319	0.326	503
1	SDSSJ001733.59+004030.4	DA/M	51795	0389	614	10918	7.180	0.270	0.02215	695	4	0.319	0.326	469
0	SDSSJ001733.59+004030.4	DA/M	51795	0389	614	11302	6.860	0.200	0.02726	856	4	0.319	0.326	469

Table A6. Table *mean_param*. Contains average stellar parameters for both stellar components, as well as WDMS binary spectral types (see Rebassa-Mansergas et al. 2010 for a description) and PCEB orbital periods. The secondary star masses and radii ($M_{\rm sec}$ and $R_{\rm sec}$) are obtained from the $Sp-M-R$ relation by Rebassa-Mansergas et al. (2007). To identify PCEBs and wide WDMS binaries the column *sigma* is set to 3 and 4 (representing 3,4σ radial velocity variations), and 0 respectively, otherwise -1. To identify resolved objects we set the column *re* to 1, 0 for unresolved objects. To identify objects followed-up by our own team we set *phot* and *spec* to 1 if those have been observed photometrically and spectroscopically respectively, set to 0 otherwise. To identify WDMS binaries identified by our SEGUE survey we set *segue* to 1, 0 otherwise. Note also that the errors have not been included here but are available on *http://www.sdss-wdms.org*.

IAU name	type	$T_{\rm eff}$(wd) [K]	$\log g$	$M_{\rm wd}$ [M$_\odot$]	$R_{\rm wd}$ [$R_\odot$]	$d_{\rm wd}$ [pc]	Sp	$M_{\rm sec}$ [M$_\odot$]	$R_{\rm sec}$ [$R_\odot$]	$d_{\rm sec}$ [pc]	*sigma*	$P_{\rm orb}$ [h]	*phot*	*spec*	*re*	*segue*
SDSSJ013335.54+130357.1	DA/M	29052	7.955	0.665	0.01481	1626	2	0.431	0.445	1252	0	0	0	1	0	0
SDSSJ013356.07-091535.1	DA/M	12250	7.360	0.320	0.01970	573	8	0.120	0.114	247	-1	0	0	0	0	0
SDSSJ013418.52+010100.0	DA/M	23343	7.710	0.490	0.01608	1022	1	0.464	0.480	1146	-1	0	0	0	1	0
SDSSJ013441.30-092212.7	WD/M	12110	7.050	0.240	0.02446	2357	2	0.431	0.445	1907	-1	0	0	0	0	0
SDSSJ013504.31-085919.0	DA/M	9401	9.060	1.230	0.00538	169	4	0.319	0.326	471	-1	0	0	0	0	0
SDSSJ013716.08+000311.3	DA/M	19193	8.390	0.860	0.00983	643	2	0.431	0.445	856	0	0	0	1	0	0